ARMY RESEARCH LABORATORY

A Test Plan to Measure Metamaterial Performances

by Youn M. Lee

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14. ABSTRACT

As part of a continuing effort to improve antenna performance using metamaterials, the U.S. Army Research Laboratory (ARL) has conducted research using a rectangular-shaped capacitively coupled loop (CLL) and monopoles. Within the past few years, ARL has conducted research on three-dimensional (3-D) arrangements and random orientations of metamaterials. The rectangular-shaped metamaterials in 3-D arrangements were simulated using computer software, which showed pretty good results. Therefore, the CLL and monopoles in 3-D arrangements along with randomly oriented metamaterials were fabricated. This report provides details of our plan to characterize performance of the metamaterials by conducting experiments.

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1. Background and Introduction

For the past several years, the U.S. Army Research Laboratory (ARL) has actively engaged in research to improve antenna performance using metamaterials. Specifically, ARL has focused their metamaterial research by using a rectangular-shaped capacitively coupled loop (CLL) and short monopoles, which are placed behind each CLL (*1–3*). Previous research has been primarily focused to two-dimensional (2-D) layouts; however, within the past two years, ARL has conducted research on three-dimensional (3-D) arrangements and random orientations of metamaterial. Figure 1 shows a section of the 3-D layout of the metamaterial and figure 2 shows front view of a section of the rectangular CLL superimposed with a short monopole behind it. Figure 3 is a layout of a single unit cell of metamaterial. The High Frequency Structure Simulator (HFSS) was used to model these layouts (*4*). The computer simulated results show the predicted focusing effects of the electromagnetic wave after passing through the metamaterial layers, though only two sets of layers were simulated due to a lack of computer memory.

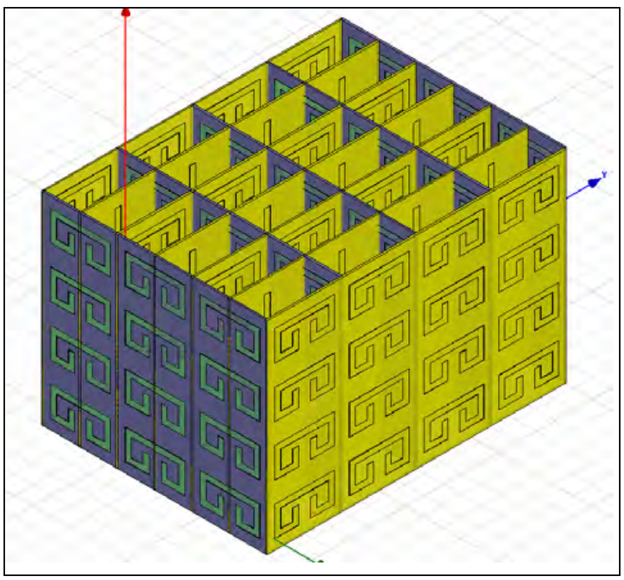

Figure 1. Three-dimensional view of a section of metamaterial stack.

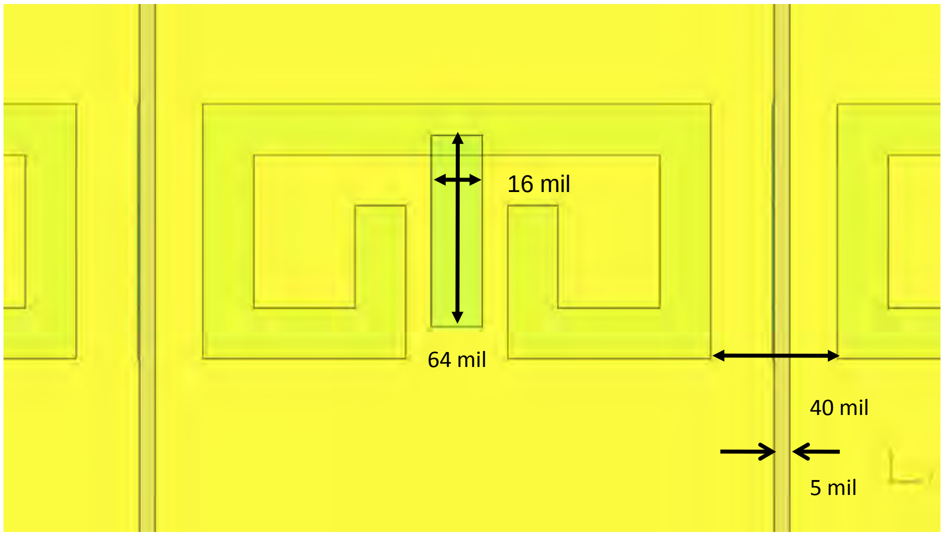

Figure 2. Front view of the split ring superimposed with a short monopole.

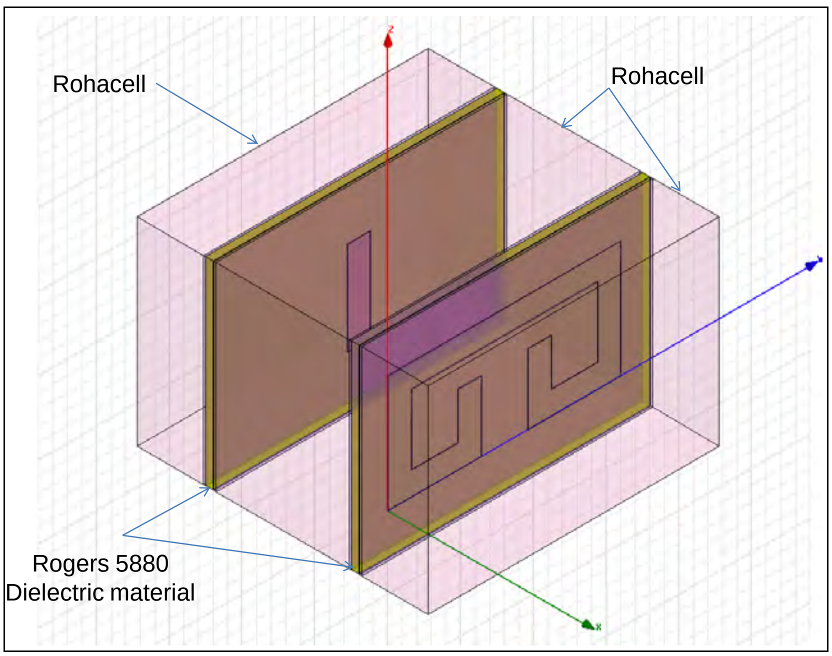

Figure 3. Three-dimensional view of a unit cell of the metamaterial.

Based on the favorable results, ARL fabricated the metamaterial model through a local vendor. This report delineates a detailed plan to evaluate the performance of the fabricated metamaterial. Section 2 covers scope of experiments and section 3 presents procedures to measure directional changes in the propagation of the electromagnetic wave through the metamaterial. Appendix A shows simulated results of the 3-D metamaterial analysis and appendix B shows photographs of fabricated 2-D metamaterial along with computed and measured results.

2. Scope of Experiments

This test plan covers test procedures for evaluating performances of the 3-D metamaterial and a pack of randomly oriented unit-cell metamaterials placed in a parallel plate. The metamaterial will be excited by an H-plane (a plane containing the magnetic field) flare sectoral horn antenna and another identical horn will be used to measure transmitted wave through the metamaterial. The primary reason for using the parallel plate is to confine the radiated field within the parallel plate in order to direct a good portion of the radiated energy toward the metamaterial. A secondary reason is to study the insertion of metamaterial in a printed Rotman lens that uses parallel plate waveguide as its medium of propagation.

To verify the simulated results, a reflected wave (S11) and transmitted wave (S21) will be measured at the ARL facility located in Aberdeen Proving Ground (APG), MD. The parallel plate will be placed at the center of the 10-ft-wide circular-shaped test fixture as shown in figure 4. Each sectoral horn antenna will be mounted on a cart, which was designed to move along the circular rail, pointing toward the center of the fixture. An antenna mounted on the cart was designed to move it along the rail, but to remain positioned perpendicular to the circular rail. Therefore, it is arranged to move toward the center or away from the plane of the parallel plate.

The center frequency of the measurements will be 13 GHz, but discrete frequency, rather than swept, measurements will be made from 10 to 15 GHz at a predetermined frequency interval to create about 50 data points per given orientation relative to the transmitting antenna position. A transmitted wave will be measured at a 5° interval by moving the receiving antenna along the circular rail at the selected frequency.

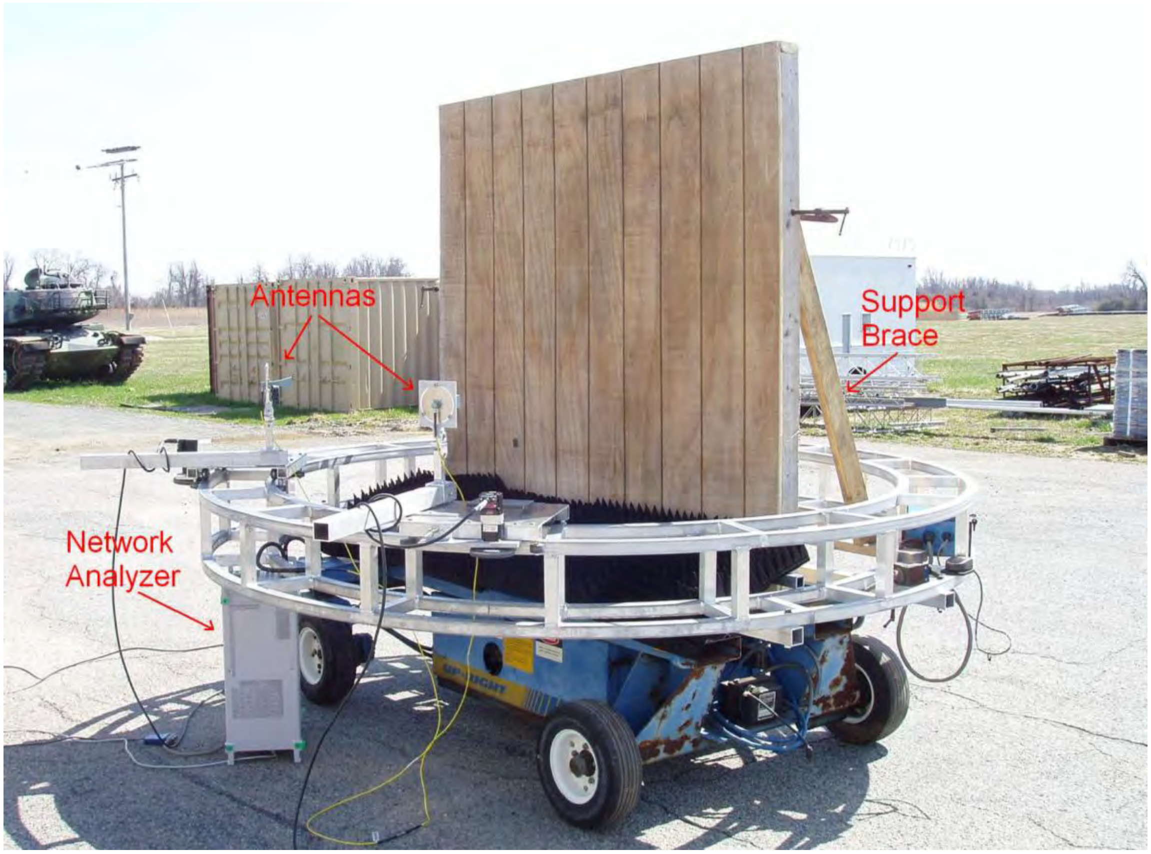

Figure 4. The picture shows the test fixture in which 10-ft circular plates will be placed at the center. The carts will be placed on the circular rail. A sectoral antenna will be attached to a cart. A wall at the center will be replaced with circular parallel plates.

3. Procedures of Experiments

3.1 Preparation for the Experiment

The following steps will be used to prepare the experiment:

1. A separation distance of 2 in will be kept between the two 8-ft-diameter circular parallel plates. This distance will be maintained by using spacers made of small poplar tree blocks or Rohacell, which has a very low dielectric constant. An adequate number of spacers will be placed to maintain the necessary height and to avoid drooping. The top circular plate will need to be removed and then replaced fairly frequently; therefore, one should attach a lumber or a beam on the top plate so that it can be hoisted.

2. Initially, the transmitting antenna and receiving antenna will be aligned at the opposite ends of the parallel plate. A line will be drawn on the parallel plate as a reference for this alignment. The transmitting antenna can be moved toward the center of the parallel plate along the reference line, if necessary.
3. Microwave absorber material will be cut to a 2-in height and be at least 1 ft wide and 6 in deep. We will prepare several pieces for testing.
4. We will calibrate the network analyzer from 10–15 GHz. We will also test the several coaxial cables to be used to eliminate defective cables and record attenuation of these cables as a function of frequency. High quality, low loss coaxial cables should be used to minimize cable loss.
5. Several measurements will be made without the presence of the metamaterial (free space within the parallel plate) to generate baseline measurements and establish the dynamic range. We will ensure that the apertures of the transmitting and receiving horns are placed inside the parallel plate.

   Then, we will move the transmitting antenna closer toward the center by 1 ft at a time and repeat the measurement.
6. We will repeat the measurement in step 5 after placing the microwave absorber blocks. The blocks will be added until the received signal is buried under the noise. At that point, we will record the depth of the microwave absorber. We will then cut the microwave absorber so that it will have a rectangular opening of 20 inches in width and 1 inch in height at the center. The opening should be aligned with the path of the electromagnetic wave when viewed from the transmitting antenna.

3.2 Experiment Procedure

3.2.1 Measuring Metamaterial Block Response of 1-in Stack

The following procedures will be use to measure the metamaterial block response of the 1-in stack:

1. Place the box containing stacks of metamaterial at the center of the parallel plate such that broadside of the CLL and monopoles, which are bonded together as a rectangular stack, are perpendicular to the direction of propagation of the incoming wave. Place the microwave absorber with opening butted against the box containing stacks of metamaterial, facing transmitting antenna.
2. Measure S11 and S21 at 13 GHz. Add a low-noise signal amplifier in line if the S21 is buried in the noise.
3. Rotate the box 90° if the measurement fails in step 2, and measure S11 and S21.

4. Remove two stacks, one from the front and one from the back, and measure S11 and S21. Replace the removed stack with a blank Styrofoam. Continue to remove two stacks at a time as before until the S21 signal surface above the noise is about 3 dB.
5. Continue to measure S11 and S21, starting at 10 GHz up to 15 GHz in 100-MHz intervals. At each frequency step, rotate the receiving antenna in 5° intervals from 0° to 85°. Discard any set of measurements if no signal can be detected at that frequency step.
6. At 12.5, 13, and 13.5 GHz, measure the measurement in step 5 by rotating the receiving antenna from –85° to +85° to check the symmetry of the radiation pattern.

3.2.2 Measuring Metamaterial Block Response of 2-in Stack

The following procedures will be use to measure the metamaterial block response of the 2-in stack:

1. Stack the metamaterials 2 in high at the center of the parallel plate such that the broadside of the CLL and a monopole, which are bonded together as a rectangular stack, are perpendicular to the direction propagation of the incoming wave. Include a 5-mil-thick CLL strip perpendicular to the rectangular stack, just the way it was laid out in the box, but 2 in high. Place the microwave absorber on either side of the metamaterial stacks.
2. Measure S11 and S21 at 13 GHz.
3. Continue to measure S11 and S21, starting at 10 GHz up to 15 GHz in 100-MHz intervals. At each frequency step, rotate the receiving antenna in 5° intervals from 0° to 85°. Discard any set of measurements if no signal can be detected at that frequency step.
4. At 12.5, 13, and 13.5 GHz, measure the measurement in step 3 by rotating the receiving antenna from –85° to +85° to check the symmetry of the radiation pattern.

3.2.3 Measuring Randomly Oriented Metamaterial Response

The following procedures will be use to measure the randomly oriented metamaterial block response:

1. Place a 2-in-high rectangular box, without top or bottom, made of Styrofoam, Determined the size of the box based on experience gained from the previous measurements. Place the microwave absorber on either side of the metamaterial box.
2. Measure S11 and S21 at 13 GHz.
3. Continue to measure S11 and S21, starting from 10 GHz up to 15 GHz in 100-MHz intervals. At each frequency step, rotate the receiving antenna in 5° intervals from 0° to 85°. Discard any set of measurement if no signal can be detected at that frequency step.

4. Rotate the box containing the randomly oriented metamaterial unit cells in 10° increments from 0° to 90°. Measure the S11 and S21 at each increment for frequencies starting from 10 GHz to 15 GHz in 100-MHz intervals. At each frequency step, rotate the receiving antenna in 5° intervals from 0° to 85°. Discard any set of measurement if no signal can be detected at that frequency step.

4. Personnel and Activity Assignments

Youn Lee will be the director of this experiment, ensuring coordination between the test personnel and tenants for activities in the measurement area. Bob Bender is responsible for software setup, and Tim Burcham is responsible for test fixture setup and alignment. Theo Anthony is responsible for data acquisition and reducing data for reporting purposes.

Lee and Anthony will be responsible for placing the metamaterials/stacks on the parallel plate, and calibrating and operating instruments.

5. References

1. Zaghloul, A. I.; Lee, Y. Simulation of Refraction Focusing Using Negative-Refractive-Index Metamaterials. *IEEE International Symposium on Antennas and Propagation*, San Diego, CA, July 2008.

2. Zaghloul, A. I.; Lee, Y.; Weiss, S. Measurements of Refraction Focusing Using Negative-Refractive-Index Metamaterials. *USNC/URSI National Radio Science Meeting*, San Diego, CA, July 2008.

3. Wang, X.; Zaghloul, A. I. Near-Isotropic Negative Refraction Simulation in Metamaterials Using Geometrical Optics and Scattering Matrix parameters. *Invited Paper, European Conference on Antennas and Propagation*, EuCAP, Barcelona, Spain, April 2010.

4. High Frequency Structure Simulator (HFSS), version 12, ANSYS Corporation.

Appendix A. Simulated Results of the 3-D Metamaterial Analysis

Using the HFSS software, we modeled and computed a 3-D view of the metamaterial, as shown in figure 1 in the main report. Figure A-1 shows top view of the computed results overlaid with the modeled metamaterial. Figure A-2 shows a side view of the computed results overlaid with the material.

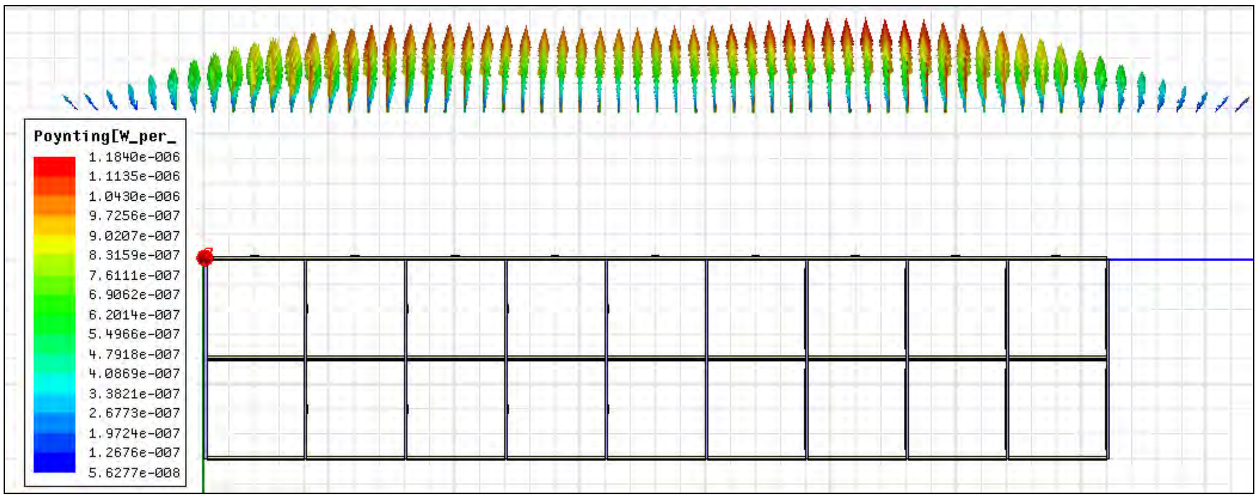

Figure A-1. Top view of the poynting vecter along with its intensity after passing through the metamaterial block.

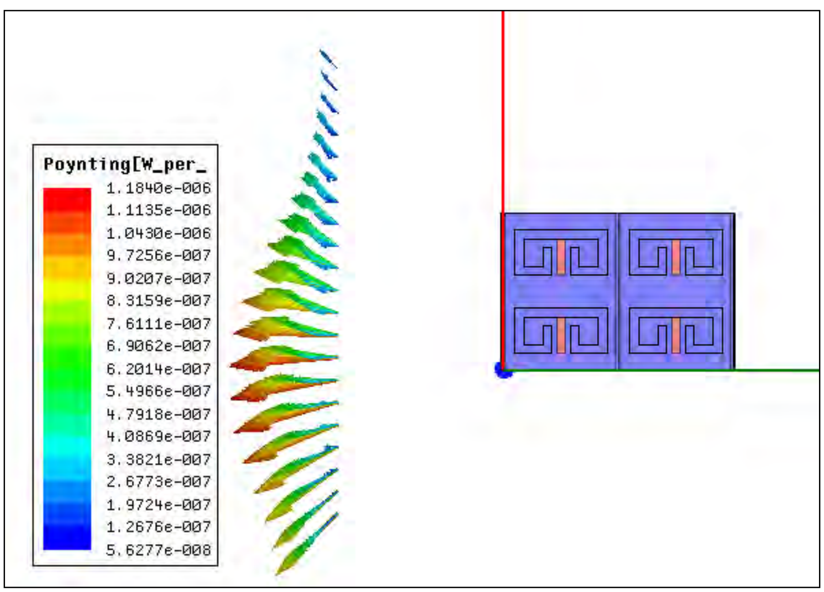

Figure A-2. Side view of the poynting vector after passing through the metamaterial block.

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Appendix B. Photographs of the Fabricated 2-D Metamaterial and Computed and Measured Results

Previously obtained results of 2-D metamaterial research of CLLs with short monopoles are shown as a reference in this appendix. These results were obtained by placing metamaterial inside a parallel plate. As can be seen in figure B-1, one small hole was drilled at one part of the parallel plate and three small holes were drilled on the other section of the parallel plate. These parts were bonded together after the metamaterial was placed in between. A small probe was inserted on the single hole, which was used to excite the parallel plate. Three small probes were also inserted and were used to detect transmitted signal. Figure B-2 shows a close-up view of fabricated split ring on Rogers 5870 dielectric material. Figure B-3 presents the HFSS simulation results of the S-parameters with the metamaterial. Computed results without the presence of the metamaterial using the HFSS are plotted in figure B-4. Figure B-5 shows measured the S-parameters of the metamaterial: Blue is S11, Pink is S21, and Green is S31. A comparison of the computed verses measured data is shown in figure B-6.

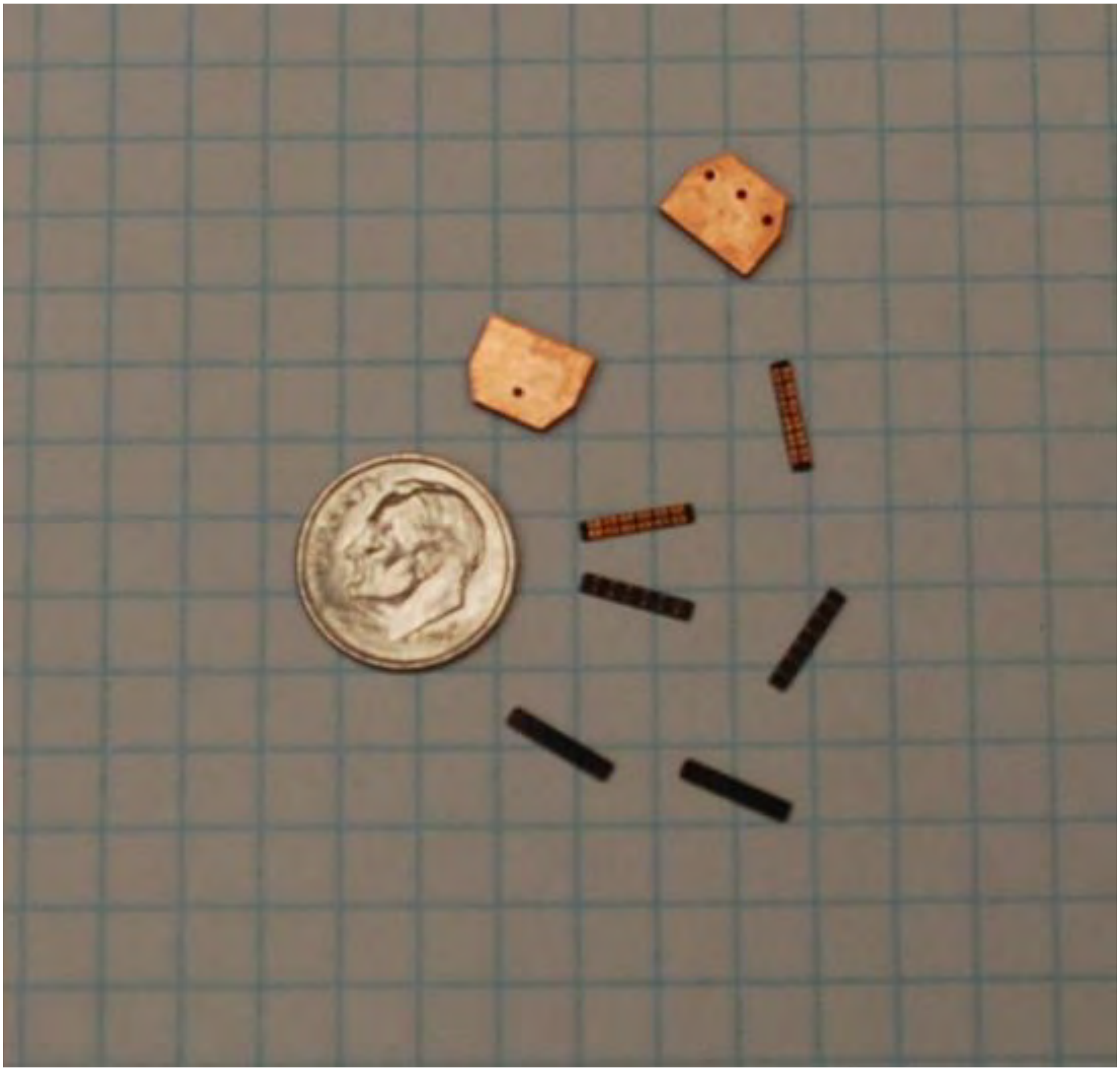

Figure B-1. Layout of the components of the metamaterial along with the two sections of the parallel plate. The metamaterials were bonded together after placing them between the two sections of the parallel plates.

Figure B-2. A close-up view of the fabricated split ring on the Rogers 5870 dielectric material.

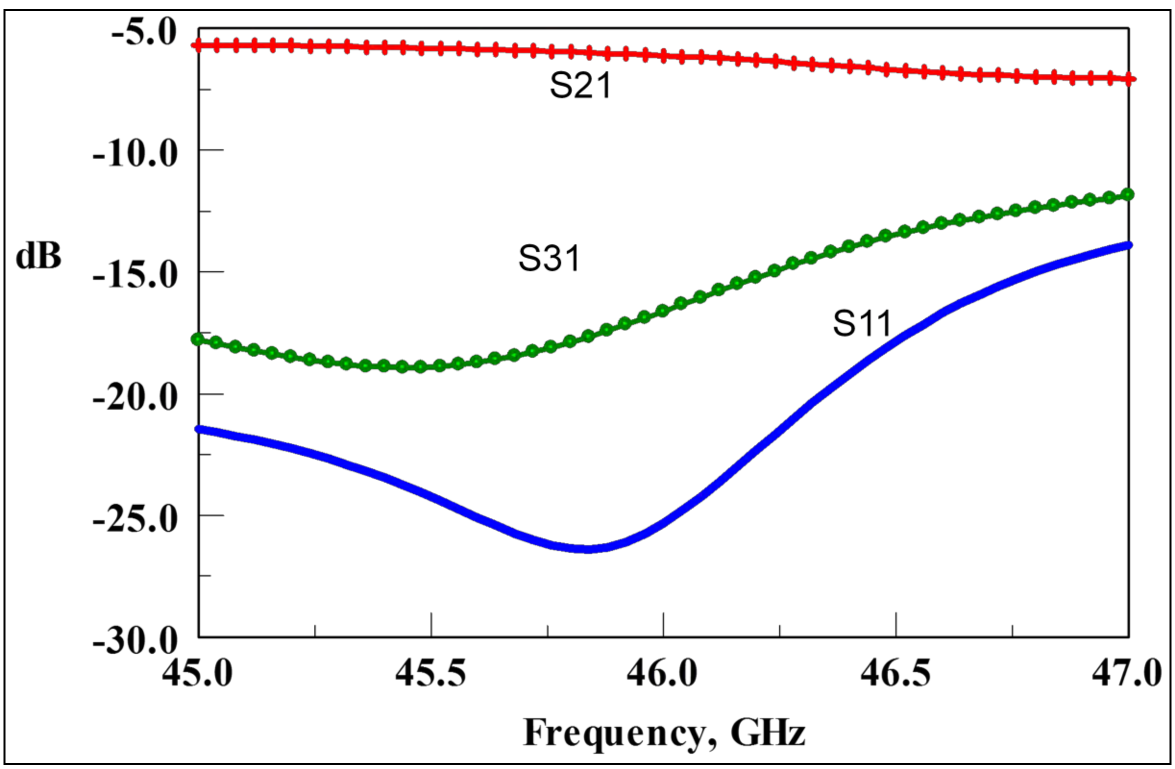

Figure B-3. HFSS simulation results of the S-parameters with the metamaterial.

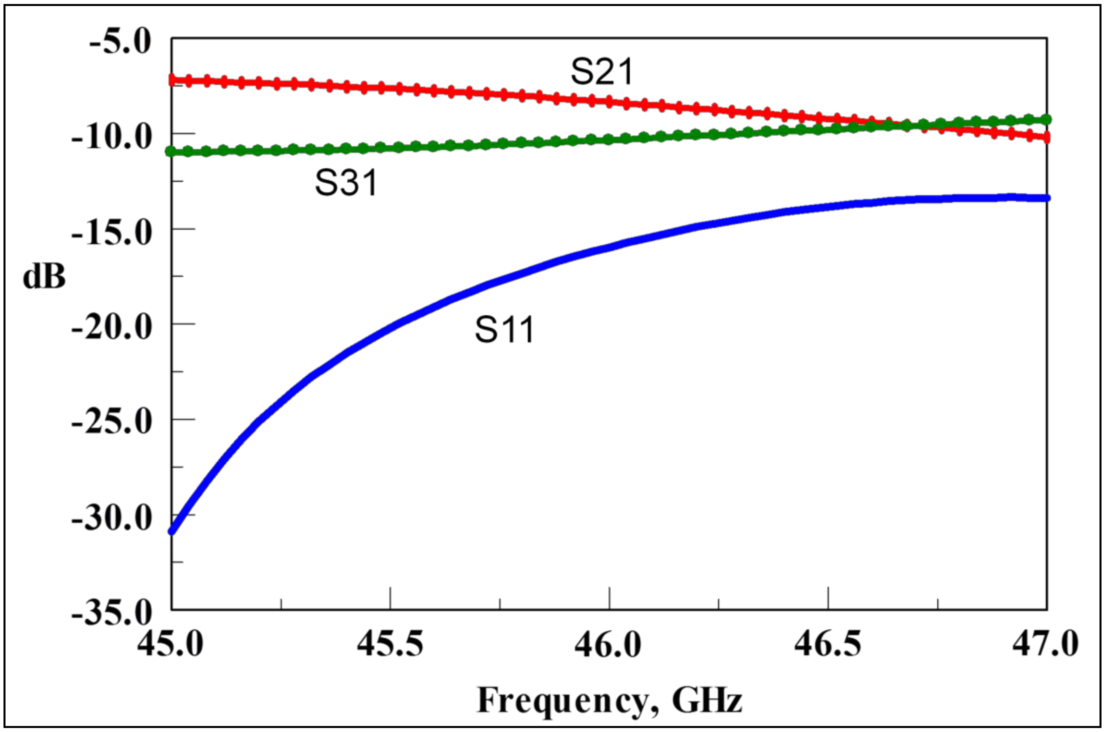

Figure B-4. Computed results without the presence of the metamaterial using HFSS.

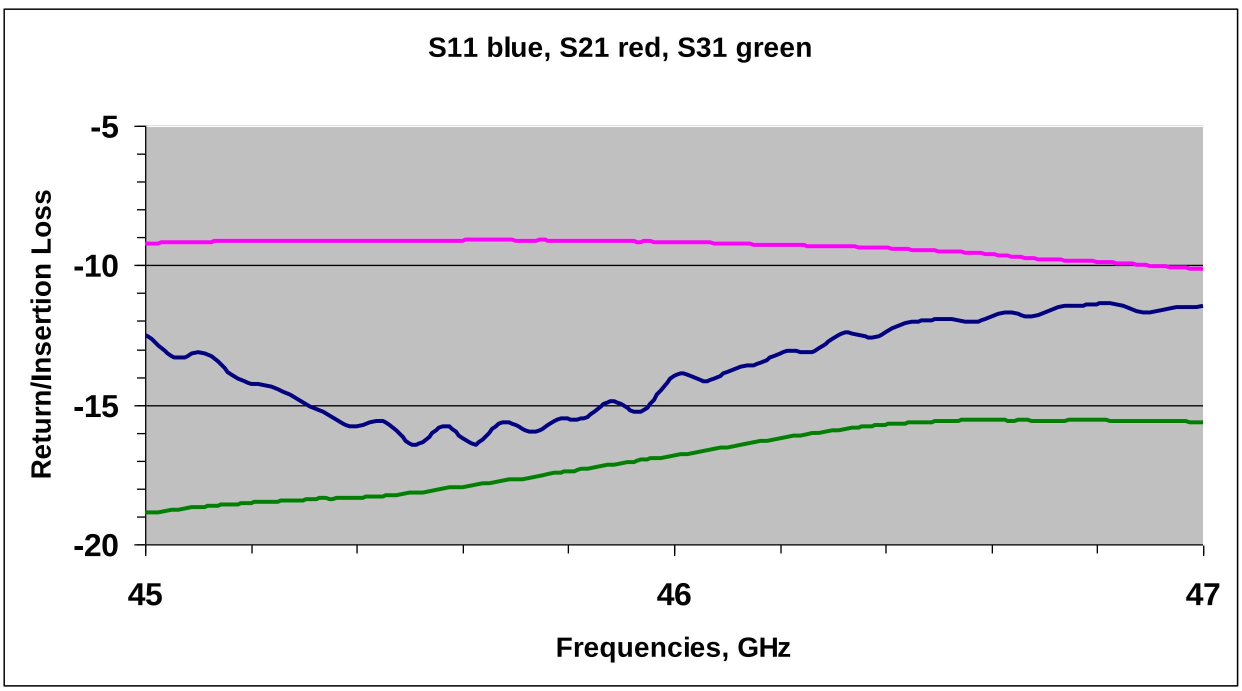

Figure B-5. Measured S-parameters of the metamaterial: blue is S11, pink is S21, and green is S31.

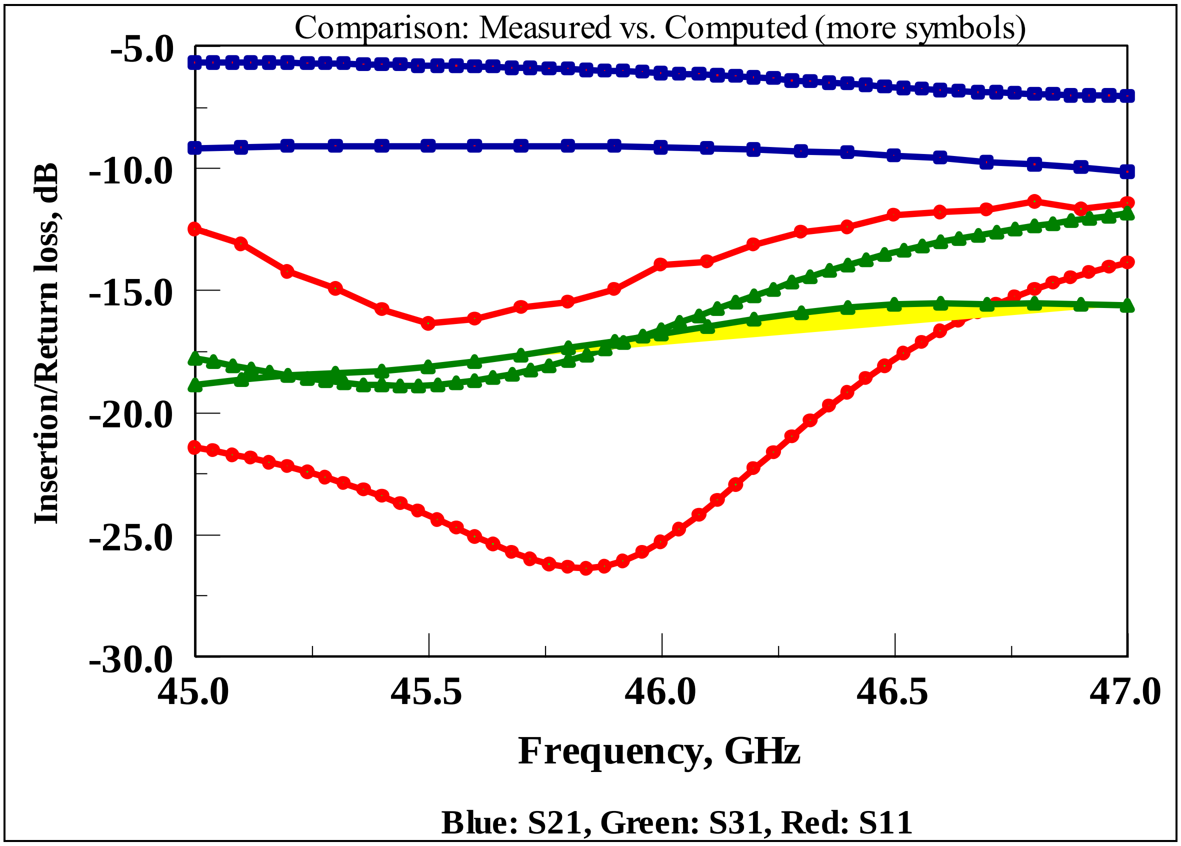

Figure B-6. Comparison of the computed vs. measured data.

List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
3-D	three-dimensional
S11	reflected wave
S21	transmitted wave
APG	Aberdeen Proving Ground
ARL	U.S. Army Research Laboratory
CLL	capacitively coupled loop
HFSS	High Frequency Structure Simulator

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